# Selected Results and Future Prospects of the COMPASS experiment at CERN 

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(9) Physics with muon beam

- Introduction
- Experimental setup
- Inclusive asymmetries
- Direct measurement of $\Delta G / G$
- Transverse spin distribution functions

2 Physics with hadron beams

- Pion Polarizabilities
- Exotic mesons
- Meson spectroscopy @ COMPASS
(3) Conclusions


## (1) Physics with muon beam

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## The spin structure of nucleons

Three DF are necessary to describe the structure of the nucleon at LO

```
Unpolarized distribution functions
\[
F_{1}(x)=u(x)+d(x)+s(x)
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```

Measured with high accuracy by unpolarized DIS experiments

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Measured with high accuracy by unpolarized DIS experiments


Only measurable in polarized semi-inclusive DIS
Almost unknown

## Where does the spin of the nucleons come from?

$$
\frac{1}{2}=\frac{1}{2} \Delta \Sigma+\Delta G+L_{q}+L_{g}
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## $\Delta \Sigma$

- Static quark model:
$\Delta \Sigma=\Delta u+\Delta d=1$
- Weak baryon decays:
$\Delta \Sigma \simeq 0.58(\Delta s=0)$
- QCD NLO fits: $\Delta \Sigma \simeq 0.3$
- Why such a discrepancy?
- $\Delta s$ large and $<0$ ?
- axial anomaly ( $\Delta G \simeq 1.5-2$ )?


## $\Delta G ?$

- Fit to $g_{1}(x)$ data
- Open charm
- High- $p_{T}$ pair production

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$$
L_{q, g} ?
$$

- Generalized PDF


## The COMPASS Experimental Setup (2004 Layout)

```
LAS:
p<60 GeV/c
Int. mag. field: 1 T m
Part. ident.: RICH1, muF1
muF1
```


## SAS:

p > $10 \mathrm{GeV} / \mathrm{c}$
Int. mag. field: 4.4 T m
Part. ident.: muF2
$\mu$ filter 2


Detailed description in NIM A577 (2007) 455-518

## The Polarized Target



- 2 (3 from 2006) cells oppositely polarized
- Acceptance: 70 mrad (180 mrad from 2006)
- ${ }^{6}$ LiD or $\mathrm{NH}_{3}$ target materials
- ${ }^{6}$ LiD polarization $>50 \%$
- 2.5 T solenoid or 0.5 T dipole fields
- Polarization reversal by field rotation every ~ 8 hours
- Unpolarized scattering by averaging over target cells


## Measurement of the inclusive asimmetry $A_{1}^{d}$



Very good agreement with previous measurements - most accurate data at low $x$

## The structure function $g_{1}^{d}$

$$
g_{1}^{d}\left(x, Q^{2}\right) \approx A_{1}^{d}\left(x, Q^{2}\right) \frac{F_{2}^{d}\left(x, Q^{2}\right)}{2 x\left(1+R\left(x, Q^{2}\right)\right)},
$$

$F_{2}^{d}$ from SMC parameterization, $R$ from SLAC parameterization


- Fit to world $g_{1}(x)$ data leads to two solutions:
- $\Delta \Sigma \simeq 0.28$ for $\Delta G>0, \quad \Delta \Sigma \simeq 0.32$ for $\Delta G<0 \quad(|\Delta G| \simeq 0.2-0.3)$
- Present $g_{1}(x)$ data not very sensitive to $\Delta G \rightarrow$ need for a direct measurement


## The structure function $g_{1}^{N}$

$$
g_{1}^{N}\left(x, Q^{2}\right)=\left(g_{1}^{p}+g_{1}^{n}\right) / 2=g_{1}^{d}\left(x, Q^{2}\right) /\left(1-1.5 \omega_{D}\right), \quad \omega_{D}=0.05 \pm 0.01
$$


old fit without COMPASS data

- Previous parametrizations do not reproduce COMPASS data at $x \rightarrow 0$
- New COMPASS points at low $x$ constrain $\Delta G$ to small values $(|\Delta G| \simeq 0.2-0.3)$


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Direct measurement of $\Delta G / G$ in $\mu N$ scattering though the photon-gluon fusion process

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High- $p_{T}$ hadron pairs

$\Uparrow$ Large statistics
$\Downarrow$ Physical backgrounds

- Two options:
- $Q^{2}<1(\mathrm{GeV})^{2}$
- $Q^{2}>1(\mathrm{GeV})^{2}$


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## Open charm production


$\Uparrow$ Direct tagging via $D^{0} / D^{*}$ production
$\Downarrow$ Small cross-section
$\Downarrow$ Combinatorial background

- Challenging experiment


## COMPASS results for $\triangle G / G$



## COMPASS results for $\Delta G / G$



- NLO QCD fits and direct measurements point to a small value of $\Delta G \approx 0.2-0.3$
- $\Delta G \ll 2 \rightarrow$ axial anomaly contribution small $\left(a_{0} \simeq \Delta \Sigma\right) \rightarrow$ two extreme scenarios?

$$
\begin{aligned}
\Delta \Sigma & \Delta G \quad L_{q} \quad L_{g} \\
1 / 2 & =1 / 2 \times 0.30+0.35+0+0 \\
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## Transverse spin distribution functions

Collins effect: a quark moving "horizontally" and polarized "upwards" would emit the leading meson preferentially on the "left" side of the jet

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$\phi_{S^{\prime}}$ : azimuthal angle of spin vector of fragmenting quark
$\phi_{h}$ : azimuthal angle of hadron momentum
$\phi_{C}=\phi_{h}-\phi_{S^{\prime}}$ : Collins angle
$\Phi_{S}=\phi_{h}-\phi_{S}$ : Sivers angle

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## Collins asymmetry

$$
\begin{aligned}
& N_{h}^{ \pm}\left(\Phi_{C}\right)=N_{h}^{0} \cdot\left\{1 \pm A_{C}^{h} \sin \Phi_{C}\right\} \\
& A_{\text {Coll }}=\frac{1}{f \cdot P_{T} \cdot D_{n n}} \cdot A_{C}^{h}=\frac{\sum_{a} e_{a}^{2} \Delta_{T} q_{a} \Delta D_{a}^{h}}{\sum_{a} e_{a}^{2} q_{a} D_{a}^{h}}
\end{aligned}
$$

## Sivers asymmetry

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## Collins and Sivers asymmetries from Deuteron target

- leading positive hadrons o leading negative hadrons


Published in Nucl. Phys. B765 (2007) 31-70
No significant deviation from zero in deuteron data $\rightarrow$ proton-neutron cancellation?

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## Comparison of COMPASS and HERMES data

left: leading positive hadrons right: leading negative hadrons
(Sign of Hermes points changed due to different angles convention in COMPASS)


Non-zero values are measured in proton data at large $x \rightarrow$ COMPASS 2007

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- Theoretical predictions:
- $\chi$-PT (2-loop): $\quad \alpha_{\pi}+\beta_{\pi}=0.16 \cdot 10^{-4} \mathrm{fm}^{3}, \alpha_{\pi}-\beta_{\pi}=(5.7 \pm 1.0) \cdot 10^{-4} \mathrm{fm}^{3}$
- QCM:
$\alpha_{\pi}+\beta_{\pi}=0.23 \cdot 10^{-4} \mathrm{fm}^{3}, \alpha_{\pi}-\beta_{\pi}=7.05 \cdot 10^{-4} \mathrm{fm}^{3}$
- QCD sum rules: $\alpha_{\pi}=(5.6 \pm 0.5) \cdot 10^{-4} \mathrm{fm}^{3}$
- Disp. sum rules: $\alpha_{\pi}+\beta_{\pi}=(0.166 \pm 0.024) \cdot 10^{-4} \mathrm{fm}^{3}, \alpha_{\pi}-\beta_{\pi}=(13.60 \pm 2.15) \cdot 10^{-4} \mathrm{fm}^{3}$
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- Large discrepancies between theoretical models
- $\alpha_{\pi}$ and $\beta_{\pi}$ can be measured in different ways:



## Measurement of $\alpha_{\pi}$ and $\beta_{\pi}$ in Primakoff Scattering

$$
\frac{d \sigma_{\gamma \pi}^{2}}{d E_{\gamma^{*}} d \cos \theta}=Z^{2}\left\{F_{\gamma \pi}^{p t}(\theta)+\frac{m_{\pi} E_{\gamma^{*}}}{\alpha} \cdot \frac{\alpha_{\pi}\left(1+\cos ^{2} \theta\right)+\beta_{\pi} \cos \theta}{\left[1+E_{\gamma^{*}} / m_{\pi}(1-\cos \theta)\right]^{3}}\right\}
$$

$E_{\gamma^{*}}$ and $\theta$ given in the anti-laboratory system
In the hypothesis of $\alpha_{\pi}=-\beta_{\pi}, \beta_{\pi}$ can be extracted from the ratio $R(\omega)=\frac{d \sigma_{e x p}}{d \sigma_{M C}^{p t}} \approx 1+\frac{3}{2} \frac{m_{\pi}^{2}}{\alpha} \frac{\omega^{2}}{1-\omega} \beta_{\pi} \quad\left(\omega=E_{\gamma} / E_{\text {beam }}\right.$ in labo. $)$


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- Measured at COMPASS with $190 \mathrm{GeV} \pi^{-}$beam and 3 mm thick Pb target
- Additional data collected with $190 \mathrm{GeV} \mu^{-}$beam
$\rightarrow$ point-like projectile to check systematics UNIQUE
- Denominator of $R(\omega)$ is calculated from MonteCarlo simulations
- Radiative corrections are applied to the experimental measurements to calculate $R(\omega)$
- Vacuum polarization
- Compton vertex
- Multiple photon exchange
- Screening by atomic electrons



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COMPASS $2004 \pi$-data


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Preliminary result: $\alpha_{\pi}=-\beta_{\pi}=\left(2.5 \pm 1.7_{\text {stat }} \pm 0.6_{\text {sys }}\right) \cdot 10^{-4} \mathrm{fm}^{3}$

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COMPASS $2004 \pi^{- \text {-data }}$


COMPASS $2004 \mu^{-}$data


For details, see J. Friedrich's talk this afternoon

## Mesons beyond the NQM

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- Glueballs: states with only valence gluons ( $g g, g g g$ )
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J^{P C}=0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots
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- The unabiguous experimental identification of such states represents a fundamental test of non-perturbative QCD


## Glueballs mass spectrum

Lattice calculations (numerical solution of the QCD Lagrangian over a space-time grid) provide the most accurate predictions for the glueballs spectrum
C. Morningstar and M. Peardon,


- Lower mass glueballs:
- $J^{P C}=0^{++}$scalar $M \sim 1700 \mathrm{MeV} / \mathrm{c}^{2}$
- $J^{P C}=2^{++}$tensor $M \sim 2400 \mathrm{MeV} / \mathrm{c}^{2}$
4

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- The light glueballs have conventional JPC
mixing with nearby $q \bar{q}$ mesons
- The lightest exotic glueball $\left(2^{+-}\right)$is above $4 \mathrm{GeV} / \mathrm{c}^{2}$


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Central production


WA76, WA91, NA12/2, WA102 and E690

- Large rapidity gap between scattered beam and $X$
- Beam particle looses
$\sim 10 \%$ of its energy
- Particles at large angles from $X$ decays
- Possible source of glueballs


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VES and E852

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- Beam particle looses
$\sim 10 \%$ of its energy
- Particles at large angles from $X$ decays
- Possible source of glueballs
- Foward kinematics
- Large cross-section (~mbarn)
- Need to separate particles at very small angles
- Study of $J^{P C}$-exotic mesons


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Beam PID with CEDAR counters
Fast DAQ \& high trigger rate


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Electromagnetic calorimetry
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Electromagnetic calorimetry

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(3) Conclusions

- COMPASS has extended the measured range of $g_{1}^{d}(x)$ down to $\sim 0.002$
- Statistical error on $\Delta \Sigma$ improved by a factor 2
- $98 \%$ of $\Gamma_{1}^{N}$ obtained from data (was $50 \%$ in SMC)
- Small $\Delta G(\ll 2)$ more and more likely
- axial anomaly contribution small $\left(a_{0} \simeq \Delta \Sigma\right)$
- two extreme scenarios?

$$
\begin{aligned}
& \Delta \Sigma \Delta G \quad L_{q} \quad L_{g} \\
& 1 / 2=1 / 2 \times 0.30+0.35+0+0 \\
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\end{aligned}
$$

- Data on semi-inclusive asymmetries will provide additional knowledge on the quark polarization $\rightarrow$ measurement on proton in 2007
- Collins and Sivers effects found to be compatible with zero on Deuteron $\rightarrow$ measurement on proton in 2007
- Preliminary measurement of pion polarizabilities from 2004 hadron beam data
- A wide and challenging meson spectroscopy program will start in 2008

